GERMANIUM BLOCKED IMPURITY BAND DETECTORS

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ABSTRACT

Ge:Sb BIB detectors have been fabricated by growing an Sb doped IR active layer (typically 40 micrometers) on pure Ge <111> oriented substrate wafers by Liquid Phase Epitaxy (LPE) from a Pb solution, and thinning the pure wafer to a thickness of 10 micrometers. Extended long wavelength response to ~ 50 cm^{-1} which increases rapidly with bias has been observed in Ge:Sb BIB detectors with $N_D \sim 1 \times 10^{16}$ cm^{-3}. The responsivity at long wavelengths is low and is, in part, attributed to Sb diffusion from the IR active layer into the blocking layer during LPE growth. BIB modeling indicates that this Sb concentration profile increases the electric field in the transition region and reduces the field in the blocking layer.

INTRODUCTION

The Blocked Impurity Band (BIB) detector concept was first proposed in 1980 by Petroff and Stapelbroek at the Rockwell International Science Center.[1] Since then, BIB detectors implemented in silicon (e.g. Si:As and Si:Sb) have been successfully incorporated into infrared array cameras and spectrographs on satellites such as the Space Infrared Telescope Facility (SIRTF).[2] The success of silicon BIB development is due in part to the large scale efforts in growth of ultra-pure silicon films. While growth of ultra-pure ($<10^{10}$ cm^{-3}) bulk germanium crystals has been an important achievement,[3] the growth of epitaxial layers of ultra-pure Ge has not been well established. The development of a growth process for achieving pure epitaxial Ge layers is necessary before Ge BIB detectors can be realized. Germanium BIB detectors are expected to offer extended long wavelength response (to $\lambda \geq 200\mu m$), and could potentially replace stressed Ge:Ga photoconductors as well as standard Ge photoconductors for far infrared astronomical observations.

A schematic of an n-type BIB detector is shown in Figure 1. The device is comprised of two semiconducting layers, a pure blocking layer and a doped infrared (IR) absorbing layer which serves as the active layer of the device. The active layer is doped to a donor concentration such that an impurity band is formed. This both lowers the minimum detectable photon energy and increases the linear optical absorption coefficient. The active layer contains a high concentration of n-type dopant (~ 10^{16} cm^{-3} for Ge) and a compensating p-type dopant (~ 10^{12} cm^{-3} for Ge). Under reverse bias, electrons move in the impurity band toward the positive contact and are stopped by the blocking layer. Ionized donor states are filled, leaving behind a region of negative space charge created by ionized acceptor states. This depletion region has a width (w) that depends on

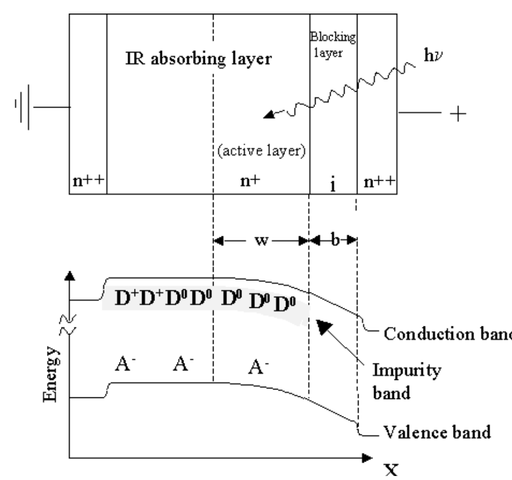

Figure 1: *Schematic of an n-type Blocked Impurity Band detector with band diagram below, shown for a device with an electric field applied. Heavily doped contacts are labeled n^{++}. D^+ = ionized donor, D^0 = neutral donor, A^- = ionized acceptor, w = depletion width.*

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applied bias (V_a), acceptor concentration (N_A), and blocking layer thickness (b) as determined by Petroff and Stapelbroek:

$$w = \left[\sqrt{\frac{2\varepsilon\varepsilon_0 (V_a - V_{bi})}{eN_A} + b^2} \right] - b \qquad (1)$$

where $\varepsilon\varepsilon_0$ is the dielectric constant, e is the electron charge, and V_{bi} is the built-in potential which is small and can be neglected. The depletion width is the active area of the device. A large depletion width requires N_A and b to be small. A Ge BIB fabricated using a film with $5x10^{11}cm^{-3}$ minority doping concentration and having a 10μm blocking layer would have a depletion width of 63μm at 1.5V applied bias according to equation 1. Using a value of α=100cm^{-1} for the linear absorption coefficient of Ge doped at $1x10^{16}cm^{-3}$ for a photon wavenumber of 50cm^{-1} (as determined by Bandaru et.al.[4]), absorption calculations show that 52% of a 50cm^{-1} photon flux incident on the detector would be absorbed in a single pass.

EXPERIMENTAL PROCEDURES

Liquid Phase Epitaxy

Epitaxial layers of Sb-doped Ge were grown from a Pb solvent by Liquid Phase Epitaxy in a tipping boat system. Pure Ge substrates ($n=2x10^{12}$ cm^{-3}) oriented to within 0.01° of the <111> were chosen as substrate (blocking layer material). LPE growth was carried out in a single zone quartz tube furnace under palladium diffusion purified H_2. Growth materials included ultra-pure Ge and 99.9999% (6N) pure Sb dissolved in 99.9999 % pure Pb (~10g). The solvent was saturated with Ge at 655°C and equilibrated for 5.5 hours. The charge was tipped onto the substrate at an undercooling of 3 °C to begin growth. Layer growth occurred as the furnace temperature was ramped down to 340 °C over 12 hours. A typical epilayer thickness is 40 μm.

Blocked Impurity Band detector fabrication

The purity of commercially available Pb has been found to be a problem, and layers grown with this solution contained a high concentration of n-type impurities,[5] ~ 10^{15} cm^{-3}. Because of the difficulty in obtaining pure Pb, an Sb-doped active layer was grown on a pure substrate, which was thinned down to form the blocking layer. The epilayer was polished and the surface was implanted with phosphorus ions (2 x 10^{14} cm^{-2} at 40 kV and 4 x 10^{14} cm^{-2} at 100 kV) at 77K. The substrate was lapped and polished to leave a 10 μm thick blocking layer. The pure side was masked around the edges with a shadow mask and phosphorus ions were implanted (2 x 10^{14} cm^{-2} at 33 kV) into this masked surface. Implanted samples were annealed at 450 ºC for 2 hours in flowing Ar gas before metallization. After annealing, 200Å Pd/4000 Å Au were sputter deposited onto both sides of the device. A finger structure shadow mask was used while depositing Pd/Au on the pure side in order to leave ~1/3 of the implanted surface area transparent to IR while still applying a relatively uniform electric field to the device.

RESULTS AND DISCUSSION

BIB detector characterization

An Sb doped germanium layer ~ 10^{16} cm^{-3} grown at 650°C was used to fabricate a BIB detector as described above. The current – voltage behavior of this detector at 2 K is shown in Figure 2(a). Under positive bias applied to the blocking layer (reverse bias for an n-type BIB) the device is blocking. It begins to break down at ~ 40 mV. Under positive bias below 40 mV the leakage current is below 10^{-14} A, the detectability limit of our electronics. The spectral response of this Ge:Sb BIB at 2K is shown in Figure 2(b) for three different applied bias values. Long wavelength response is observed relative to a standard Ge:Sb photoconductor, and the onset of photoconductivity extends to lower wavenumbers (longer wavelength) as the bias is increased.

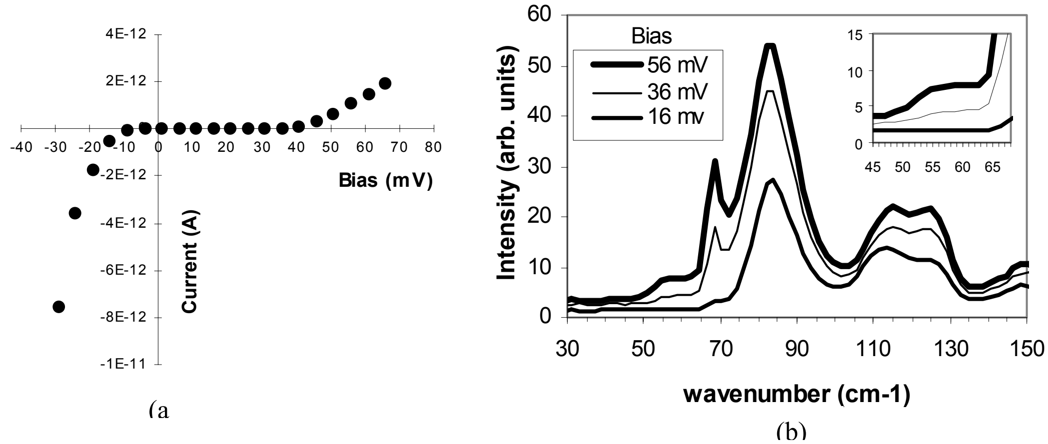

Figure 2: *(a) Dark current – voltage characteristics of a Ge:Sb BIB detector at 2 K. At very low bias the dark current is below the detection limit of our electronics. (b) Spectral response of the BIB detector at 2 K with increasing applied bias. The inset shows an enlargement of the long wavelength onset in photoconductive response and its extension*

BIB detector modeling

The distribution of Sb in doped Ge LPE layers had to be determined accurately due to its potential effect on photon absorption and electric field profiles in a BIB device. SIMS data show significant Sb diffusion into the blocking layer for layers grown at 650°C, with Sb concentration dropping an order of magnitude over 1.5 μm.[6] Layers grown at 550°C do not show significant Sb diffusion into the blocking layer. Steady state spatial electric field distributions in the absence of light have been calculated using a numerical finite difference approach.[7] Gradients in Sb concentration (N) across the interface have been considered, and are defined by a grade parameter (g) as follows:

$$N = N_1 + \frac{(N_2 - N_1)}{1 + \exp[(a - x)/g]} \tag{2}$$

where N_1 and N_2 are the layer dopings, a is the interface position, and x is the position variable.

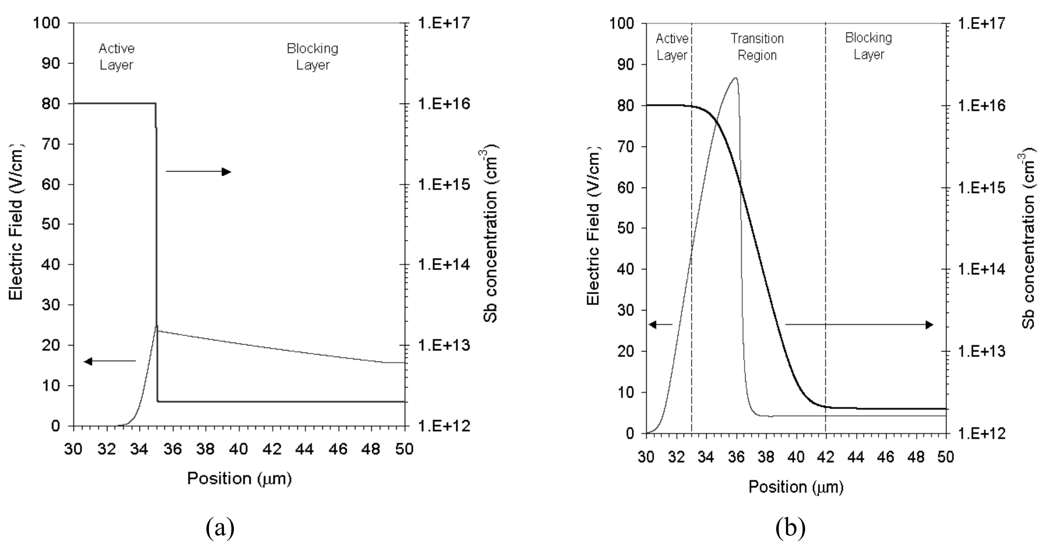

Figure 3: *Model of electric field distributions for 30 mV applied bias and Sb concentration gradients across the blocking layer/active layer for (a) a sharp gradient, g= 8x10^{-7} cm and (b) a gradient similar to that observed in epilayers grown at 650 °C, g=6x10^{-5} cm. The interface is at 35 μm. (courtesy N. M. Haegel, reference 6)*

Figure 3 (from reference 6) shows a model of the E-field distribution across a BIB detector with 30 mV applied bias. Figure 3(a) shows the E-field distribution for a sharp interface ($g=8x10^{-7}$ cm). The Sb profile in our LPE layers corresponds to the grade parameter $g=6x10^{-5}$ cm shown in Figure 3(b). The depletion width of the device would consist partly of material doped to some intermediate value between the blocking layer and the active layer. This material would have a narrower impurity band, giving rise to a reduced long wavelength response in the transition region. In addition, the extreme diffusion of Sb into the blocking layer would reduce its blocking effectiveness, and could also affect gain in the device.

CONCLUSIONS

Extended long wavelength response which increases with bias has been observed in Ge:Sb BIB detectors. The purity of the undoped LPE layers has been found to be insufficient for use as BIB blocking layers. Future efforts will focus on purification of Pb by zone refining, which would enable growth of both pure and doped layers for BIB detector fabrication. The long wavelength response of the BIB detector is lower than expected. A significant Sb concentration gradient in the transition region between the blocking layer and active layer was observed using SIMS. BIB modeling indicates that the Sb gradient increases the electric field in the transition region and reduces the field in the blocking layer. The depleted material consists partly of the transition region between the active and blocking layer. This material is doped lower than the bulk layer and may contribute to the reduced long wavelength response. We are currently trying to develop thicker Sb-doped films at lower temperatures. This is expected to improve the long wavelength response of the BIB detector.

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